DESCRIPTION

RELAXOR FERROELECTRIC SOLID-SOLUTION SINGLE CRYSTAL, DEVICE, AND METHOD OF USING DEVICE

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Technical Field

The present invention relates to relaxor ferroelectric substances which are useful in the field of optical
10 mechatronics and applicable, for example, to information devices (IT devices) such as cell phones. Also, it relates to optical devices and ferroelectric devices which use such a relaxor ferroelectric substance as well as a method of using these devices.

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Background Art

Relaxor ferroelectric substances have been used as capacitor materials because of their high permittivity as well
20 as because of low temperature dependence and low electric-field dependence of their permittivity. Also, they have been used as piezoelectric/electrostrictive material to take full advantage of their excellent electromechanical coupling factor. Furthermore, their excellent piezoelectric characteristics
25 have been used, for example, for ultrasonic transducers (e.g., Patent Document 1).

Patent Document 1: Japanese National Phase Laid-Open Patent Publication No. 2001-509312

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Disclosure of the Invention

The present invention is based on optical characteristics and dielectric characteristics of a relaxor ferroelectric
35 solid solution single crystal newly found by the inventors and

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an objective of the present invention is to provide a relaxor ferroelectric solid solution single crystal which has unique optical characteristics and dielectric characteristics. Another objective of the present invention is to provide a

5 device which uses the relaxor ferroelectric solid solution single crystal as well as to provide a method of using the device.

To achieve the above objectives, according to one aspect

10 of the present invention, there is provided a relaxor ferroelectric solid solution single crystal. The relaxor ferroelectric solid solution single crystal is capable of making transitions, at temperatures below the Curie temperature, between a first state which has a high

15 permittivity and blocks optical transmission and a second state which has a low permittivity and allows optical transmission. The relaxor ferroelectric solid solution single crystal undergoes a transition to the second state if an electric field above a threshold is applied in the first state.

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Preferably, the relaxor ferroelectric solid solution single crystal undergoes a transition to the first state if heated to or above the Curie temperature in the second state. Then, the relaxor ferroelectric solid solution single crystal

25 provided by the present invention will be capable of making transitions between the first state and second state reversibly.

Preferably, the relaxor ferroelectric solid solution

30 single crystal is made of a lead-based complex perovskite compound. The lead-based complex perovskite compound may be expressed as any of $(1-x)Pb(Mg_{1/3}Nb_{2/3})O_3 \cdot xPbTiO_3$, $(1-x)Pb(Zn_{1/3}Nb_{2/3})O_3 \cdot xPbTiO_3$, and $(1-x)Pb(In_{1/2}Nb_{1/2})O_3 \cdot xPbTiO_3$, where x represents a composition ratio of $PbTiO_3$ in the lead-based

35 complex perovskite compound. Hereinafter $(1-$

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x)Pb(Mg$_{1/3}$Nb$_{2/3}$)O$_3$·xPbTiO$_3$ will be abbreviated to PMN-PT, (1-x)Pb(Zn$_{1/3}$Nb$_{2/3}$)O$_3$·xPbTiO$_3$ to PZN-PT, and (1-x)Pb(In$_{1/2}$Nb$_{1/2}$)O$_3$·xPbTiO$_3$ to PIN-PT. The PMN-PT, PZN-PT and PIN-PT are capable of making transitions between the first

5   state and second state within a range of the composition ratio x of between 0.1 and 0.2 (exclusive) by the application of an electric field.

Variations in characteristics of a lead-based complex
10   perovskite compound due to differences in the composition ratio x will be described below by citing PMN-PT, and the same applies to PZN-PT and PIN-PT. Fig. 2 is a graph showing temperature dependence of relative permittivity of approximately 100-μm-thick PMN-PT (001) plates which differ
15   from each other in composition ratio x. The relative permittivity was measured by applying an AC electric field with a frequency of 10 kHz, 100 kHz, or 1 MHz to the PMN-PT (001) plates through electrodes attached to both sides of the PMN-PT (001) plates. The strength of the applied electric
20   field was varied with the thickness of the measured plates, with the maximum electric field being 10 V/cm.

As can be seen from Fig. 2, the higher the frequency of the applied electric field, the lower the relative
25   permittivity. It can also be seen from Fig. 2, that the relative permittivity is comparatively large when the composition ratio x is 0.1 or 0.2. The relative permittivity (ε_r) is obtained by dividing permittivity (ε) by the permittivity of vacuum (ε_0) (i.e., $\varepsilon_r = \varepsilon/\varepsilon_0$), and thus a
30   substance with a high permittivity generally has a high relative permittivity. It should be noted in Fig. 2 that the relative permittivity exceeds 10,000 at a temperature of between 25°C and 100°C when x = 0.1. It should also be noted that when x = 0.2, the relative permittivity reaches a peak
35   exceeding 10,000 at a temperature of 100°C and lowers to

3

approximately 5,000, less than half the peak, at a temperature of 50°C.

Figs. 3(a) and 3(b) are phase diagrams of a PMN-PT solid solution single crystal, where Fig. 3(b) is a partial enlarged view of Fig. 3(a). In Figs. 3(a) and 3(b), the abscissa represents the composition ratio x of $PbTiO_3$ (PT) in the PMN-PT while the ordinate represents temperature. As shown in Fig. 3(a), the PMN-PT solid solution single crystal takes on any of a cubic phase, tetragonal phase, and pseudocubic/rhombohedral phase depending on the composition ratio and temperature. In Figs. 3(a) and 3(b), a boundary between the tetragonal phase and cubic phase and a boundary between the pseudocubic/rhombohedral phase and cubic phase are represented by a boundary line α, and a boundary between the pseudocubic/rhombohedral phase and tetragonal phase is represented by an MPB (morphotropic phase boundary) line. When the composition ratio is constant, a crystal phase change occurs from a tetragonal phase or pseudocubic/rhombohedral phase to a cubic phase, or from a cubic phase to a tetragonal phase or pseudocubic/rhombohedral phase on reaching a certain temperature. The temperature at which the crystal phase change occurs is the Curie temperature.

The PMN-PT solid solution single crystal in the cubic phase has light blocking properties. That is, the PMN-PT solid solution single crystal blocks optical transmission regardless of its composition ratio x when its temperature is equal to or higher than the Curie temperature. On the other hand, when its temperature is below the Curie temperature, the PMN-PT solid solution single crystal allows optical transmission at least partially if its composition ratio x is 0.2 or higher.

The PMN-PT solid solution single crystal in the

4

pseudocubic/rhombohedral phase exhibits electric field hysteresis when its composition ratio x is larger than 0.1 and smaller than 0.2. The PMN-PT solid solution single crystal with its composition ratio x being larger than 0.1 and smaller than 0.2 is capable of making transitions between a first state which has a high permittivity and blocks optical transmission and a second state which has a low permittivity and allows optical transmission. Also, the PMN-PT solid solution single crystal with its composition ratio x being larger than 0.1 and smaller than 0.2 has a memory effect. The memory effect consists in that at a temperature below the Curie temperature, once an electric field above a threshold is applied to the PMN-PT solid solution single crystal, even if the magnitude of the electric field is increased or decreased subsequently, the PMN-PT solid solution single crystal does not make a transition from the second state to the first state.

As shown in Fig. 3(b), when the composition ratio x is 0.1 or below, the Curie temperature becomes 40°C or below, which is equal to or close to room temperature. When heated to or above the Curie temperature, the PMN-PT solid solution single crystal changes to a cubic phase in which it blocks optical transmission. Thus, when the Curie temperature is equal to or close to room temperature, even if the PMN-PT solid solution single crystal is caused by the application of an electric field above the threshold to make a transition to the state which has a low permittivity and allows optical transmission, it returns to the first state which allows optical transmission, at a temperature equal to or close to room temperature. This hampers the memory effect. Thus, in order for the memory effect to be produced properly, it is preferable that the composition ratio x is larger than 0.1. In other words, in order for the memory effect to be produced properly, preferably the composition ratio x is set such that the Curie temperature will be higher than 40°C.

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Preferably a lead-based complex perovskite compound of the relaxor ferroelectric solid solution single crystal is a pseudocubic/rhombohedral phase (001) plate. In the pseudocubic/rhombohedral phase (001) plate, an engineered domain structure called an oblique field prevents movement of domain walls caused by the application of an electric field. Consequently, the relaxor ferroelectric solid solution single crystal exhibits not only unique optical characteristics and ferroelectric characteristics, but also good actuator characteristics due to a high electromechanical coupling factor and good mechanical strain characteristics of the pseudocubic/rhombohedral phase (001) plate.

According to another aspect of the present invention, there is provided a device which uses the relaxor ferroelectric solid solution single crystal. Preferably the device uses at least optical characteristics of the relaxor ferroelectric solid solution single crystal. Alternatively, the device may use not only the optical characteristics, but also changes in dielectric characteristics of the relaxor ferroelectric solid solution single crystal taking place with changes in the optical characteristics.

According to still another aspect of the present invention, there is provided a method of using a device that incorporates the relaxor ferroelectric solid solution single crystal. The method includes: applying an electric field above a threshold to the relaxor ferroelectric solid solution single crystal in the device to cause the relaxor ferroelectric solid solution single crystal to make a transition from the first state to the second state; and heating the relaxor ferroelectric solid solution single crystal in the device to or above the Curie temperature to cause the relaxor ferroelectric solid solution single crystal

6

to make a transition from the second state to the first state.

Brief Description of the Drawings

5   Fig. 1 is a side view of an optical device according to an embodiment of the present invention;

Fig. 2 is a graph showing temperature dependence of relative permittivity of PMN-PT (001) plates with composition ratio x of 0 to 0.9;

10   Figs. 3(a) and 3(b) are phase diagrams of a PMN-PT solid solution single crystal;

Figs. 4(a) to 4(c) are polarized photomicrographs taken of device bodies of optical devices according to example 1 and comparative examples 1 and 2 with no electric field being

15   applied;

Figs. 5(a) to 5(c) are polarized photomicrographs taken of a device body of an optical device according to comparative example 3;

Fig. 6 is a graph showing electric-field dependence of

20    $\varepsilon_{(E)}/\varepsilon_{(0)}$ of optical devices according to comparative examples 3 and 4;

Figs. 7(a) to 7(d) are polarizing microscopes taken of the device body in the optical device according to example 1 with an electric field which changes unidirectionally from 0

25   kV/cm to 8.2 kV/cm being applied to the optical device;

Fig. 8 is a graph showing electric-field dependence of relative permittivity of the optical device according to example 1;

Figs. 9(a) and 9(b) are polarized photomicrographs taken

30   of the device body in the optical device according to example 1 with an electric field which changes unidirectionally from 8.2 kV/cm to 0 kV/cm being applied to the optical device;

Figs. 10(a) to 10(d) are polarized photomicrographs taken of the device body in the optical device according to example

35   1 with an electric field which changes unidirectionally from 0

7

kV/cm to -8.2 kV/cm being applied to the optical device;

Figs. 11(a) to 11(c) are polarized photomicrographs taken of the device body in the optical device according to example 1 with no electric field being applied;

Fig. 12(a) is a graph showing temperature dependence of relative permittivity according to example 1, and Fig. 12(b) is a graph showing temperature dependence of dielectric loss tangent according to example 1;

Fig. 13 is a polarization vs. electric field hysteresis curve according to example 1;

Figs. 14(a) to 14(c) are polarized photomicrographs taken of the device body in the optical device according to example 1 with no electric field being applied after the optical device is heated to or above the Curie temperature;

Fig. 15 is a graph showing electric-field dependence of relative permittivity of the optical device according to example 1 after the optical device is heated to or above the Curie temperature;

Fig. 16 is a graph showing electric-field dependence of relative permittivity of the optical device according to example 2; and

Figs. 17(a) to 17(d) are polarizing microscopes taken of the device body in the optical device according to example 2 by applying an electric field which changes unidirectionally from 0 kV/cm to 11.7 kV/cm and then unidirectionally from 11.7 kV/cm to 0 kV/cm.

Best Mode for Carrying out the Invention

An embodiment of the present invention will be described below.

An optical device 10 according to the embodiment shown in Fig. 1 has a device body 20 and a pair of transparent electrodes 30 and 40. The device body 20 is a thin PMN-PT

8

(001) plate. The number (001) in the PMN-PT (001) plate is an
index of a crystal face. The transparent electrodes 30 and 40
are provided on both upper and lower faces of the device body
20. The transparent electrodes 30 and 40 are made of gold by
5   a physical film forming process such as sputtering or vapor
deposition.

Optical characteristics of the optical device 10 were
observed under a polarizing microscope. More specifically, as
10   shown in Fig. 1, the optical device 10 was placed on a
transparent glass plate 100 in such a way as to sit astride a
pair of glass supports 110 mounted atop the glass plate 100.
Then, the optical device 10 was observed through crossed Nicol
prisms under the polarizing microscope by illuminating the
15   optical device 10 with polarized light from a light source 200
through the transparent glass plate 100 from below.
Incidentally, the number <001> in Fig. 1 is an index of a zone
axis.

20   The transparent electrodes 30 and 40 are connected to a
DC power supply (not shown) via lead wires and variable
resisters (not shown). Voltage of different values can be
applied between the transparent electrodes 30 and 40. A
switching circuit (not shown) is attached to the lead wires.
25   A positive or negative voltage can be applied between the
transparent electrodes 30 and 40 through operation of the
switching circuit. The transparent electrodes 30 and 40 also
function as electrodes for use to measure the permittivity of
the device body 20 (PMN-PT). Besides, they are also used as
30   capacitor output terminals when the optical device 10 is not
only used as a device which utilizes the optical
characteristics of the PMN-PT, but also used in the manner of
an electronic circuit as a device which utilizes changes in
the dielectric characteristics of the PMN-PT taking place with
35   changes in the optical characteristics.

Examples and comparative examples of the present
invention will be described below. Incidentally, observations
and measurements were conducted at room temperature (25°C)
5   unless otherwise stated.

Optical devices according to examples 1 and 2 and
comparative examples 1 to 4 were created using a 122-μm thick
device body made of a PMN-PT (001) plate. The composition
10   ratio x of $PbTiO_3$ in the PMN-PT was 0.15 in example 1, 0.13 in
example 2, 0.2 in comparative example 1, 0.28 in comparative
example 2, 0.1 in comparative example 3, and 0.06 in
comparative example 4.

15   Fig. 8 shows changes in the relative permittivity of the
device body (PMN-PT) in the optical device according to
example 1, measured by applying an electric field which
changes unidirectionally from 0 kV/cm to 8.2 kV/cm and then
unidirectionally from 8.2 kV/cm to -8.2 kV/cm. Incidentally,
20   the PMN-PT in the device body before the application of the
electric field was in a state in which it had a high
permittivity and blocked optical transmission.

Figs. 4(a) to 4(c) show results obtained by observing the
25   device bodies of the optical devices according to example 1
and comparative examples 1 and 2 through crossed Nicol prisms
under the polarizing microscope with no electric field being
applied. Fig. 4(a) shows an observation result of the optical
device 10 according to example 1, where optical transmission
30   is blocked throughout the entire area. Fig. 4(b) shows an
observation result of the optical device according to
comparative example 1, where optical transmission is allowed
partially. Fig. 4(c) shows an observation result of the
optical device according to comparative example 2, where
35   optical transmission is allowed throughout the entire area.

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Figs. 11(a) to 11(c) show results obtained by observing the device body of the optical device according to example 1 through crossed Nicol prisms under the polarizing microscope

5 with no electric field being applied, as in the case of Fig. 4(a). However, Fig. 11(a) shows an observation result at a stage rotation angle of 0°, Fig. 11(b) shows an observation result at a stage rotation angle of 22.5°, and Fig. 11(c) shows an observation result at a stage rotation angle of 45°.

10 As shown in Figs. 11(a) to 11(c), dark-field image is observed at any of the rotation angles without any extinction position or diagonal position. The results indicate that the PMN-PT in the optical device according to example 1 blocks optical transmission when no electric field is applied.

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It is probably due to disorderly domain arrangement or small domain size that in Figs. 11(a) to 11(c), the PMN-PT in the optical device according to example 1 does not allow optical transmission when no electric field is applied. In

20 the optical device according to example 1, when no electric field is applied, the PMN-PT has a relative permittivity as high as around 9,500 (9,000 to 10,000), as shown in Fig. 8. At this time, the temperature dependence of relative permittivity and dielectric loss tangent of the PMN-PT shows a

25 Vogel-Fulcher type dielectric dispersion peculiar to a relaxor as shown in Figs. 12(a) and 12(b). The temperature dependence of relative permittivity and dielectric loss tangent was measured with an LCR meter by applying an AC electric field rather than a DC electric field to the PMN-PT. The strength

30 of the applied electric field was 10 V/cm and the frequency used was 1 kHz, 10 kHz, 100 kHz, or 1 MHz.

The polarizing microscope observations described above and below employ a halogen light source with a wavelength

35 range of 400 to 600 nm centered around 540 nm. In drawings

11

which show results of the polarizing microscope observations, reference numeral A denotes an analyzer and P denotes a polarizer. Also, drawings which show results of polarizing microscope observations carried out by applying an electric field also contain a symbol which indicates the direction of application of the electric field. Under crossed Nicol prisms, the analyzer A and polarizer P are used by being arranged perpendicular to each other with a specimen placed between them. If the specimen is optically isotropic, the observation under the polarizing microscope results in a dark field. If the specimen is optically anisotropic, the observation results in a bright field. Generally, a ferroelectric specimen is an anisotropic body, but if the polarizer P is set in the direction of polarization, the observation results in a dark field. This phenomenon is known as extinction. The crystal phase of the PMN-PT in the optical device according to example 1 is a rhombohedral phase at room temperature (25°C) and the polarization direction of the PMN-PT (001) plate in a rhombohedral phase coincides with a direction of <110>. Thus, a dark field appears at a position inclined at 45° from the x axis and a bright field appears at a position inclined at 60°or 30° from the x axis. The brightest position is known as a diagonal position. In a plate in a rhombohedral phase (001), the diagonal position appears on the x or y axis.

Incidentally, to obtain observation results shown in Figs. 9 and 10 (described later), the analyzer A and polarizer P are placed at an angle of 60°. from a reference position to suit observation of the PMN-PT in a tetragonal phase. In the case of a PMN-PT (001) plate in a tetragonal phase, an extinction position appears on the x or y axis, and a bright-field image is observed between the x and y axes. When the composition ratio of $PbTiO_3$ in the PMN-PT is somewhat high, the crystal phase of the PMN-PT at ordinary temperature is the tetragonal phase rather than the rhombohedral phase as shown in Fig. 3(a).

12

Also, when a very strong electric field is applied, the crystal phase of the PMN-PT changes from the rhombohedral phase to the tetragonal phase.

5   Figs. 5(a) to 5(c) show results obtained by observing a device body of an optical device according to comparative example 3 through crossed Nicol prisms under the polarizing microscope. Fig. 5(a) shows an observation result obtained with no electric field applied, where optical transmission is
10   blocked throughout the entire area. Fig. 5(b) shows an observation result obtained at a diagonal position with a 23 kV/cm electric field applied, where a bright-field image is observed. Fig. 5(c) shows an observation result obtained at an extinction position with a 23 kV/cm electric field applied,
15   where a dark-field image is observed.

     Fig. 6 is a graph showing electric-field dependence (described later) of change in the permittivity of optical devices according to comparative examples 3 and 4. The change
20   in the permittivity is represented by $\varepsilon_{(E)}/\varepsilon_{(0)}$ and obtained by dividing $\varepsilon_{(E)}$ by $\varepsilon_{(0)}$, where $\varepsilon_{(0)}$ is the permittivity of the PMN-PT measured by applying a 10 V/cm AC electric field with a frequency of 1 MHz at room temperature (25°C) and $\varepsilon_{(E)}$ is the permittivity of the PMN-PT measured by applying a DC electric
25   field E at room temperature (25°C). In Fig. 6, the abscissa represents the strength of the DC electric field E applied to the PMN-PT while the ordinate represents $\varepsilon_{(E)}/\varepsilon_{(0)}$. As shown in Fig. 6, $\varepsilon_{(E)}/\varepsilon_{(0)}$ changes comparatively gently according to the strength of the applied electric field both in comparative
30   examples 3 and 4.

     It can be seen from the results shown in Figs. 5(a) to 5(c) and Fig. 6 that the PMN-PT of the optical device according to comparative example 3 blocks optical transmission
35   when no electric field is applied, and allows optical

13

transmission when a 23 kV/cm electric field is applied. However, the PMN-PT of the optical devices according to comparative examples 3 and 4 do not exhibit electric field hysteresis.

Figs. 7(a) to 7(d) show results obtained by observing the device body of the optical device according to example 1 through crossed Nicol prisms under the polarizing microscope with an electric field which changes unidirectionally from 0 kV/cm to 8.2 kV/cm being applied to the optical device. Fig. 7(a) shows an observation result obtained with no electric field applied. Fig. 7(b) shows an observation result obtained by applying a 1.6 kV/cm electric field. Fig. 7(c) shows an observation result obtained by applying a 4.9 kV/cm electric field. Fig. 7(d) shows an observation result obtained by applying an 8.2 kV/cm electric field.

When an electric field above a threshold (2 kV/cm, in example 1) is applied, the PMN-PT in the device body makes a transition from a state in which it blocks optical transmission to a state in which it allows optical transmission as shown in Figs. 7(c) and 7(d). At the same time, the relative permittivity of the PMN-PT is approximately halved to 6,000 (5,000 to 7,000) as shown in Fig. 8. Even if the applied electric field further increases in the positive direction, the optical transmission remains allowed and the relative permittivity remains low while decreasing gradually.

Fig. 13 is a polarization vs. electric field hysteresis curve of the PMN-PT in the optical device according to example 1. The polarization vs. electric field hysteresis curve was plotted in a 50-Hz AC electric field using a known Sawyer-Tower circuit. As can be seen from Fig. 13, the state which has a low permittivity and allows optical transmission is stored by memory effect. Thus, even if the strength of the

14

applied electric field is increased or decreased, the state which has a low permittivity and allows optical transmission is maintained.

5   Figs. 9(a) and 9(b) show results obtained by observing the device body of the optical device according to example 1 through crossed Nicol prisms under the polarizing microscope with an electric field which changes unidirectionally from 8.2 kV/cm to 0 kV/cm being applied to the optical device. Fig.
10   9(a) shows an observation result obtained by applying an 8.2 kV/cm electric field. Fig. 9(b) shows an observation result obtained with no electric field applied. When an electric field which changes unidirectionally from 8.2 kV/cm to 0 kV/cm is applied in this way, the optical transmission remains
15   allowed as shown in Figs. 9(a) and 9(b) with the permittivity kept low as shown in Fig. 8.

       Figs. 10(a) to 10(d) show results obtained by observing the device body of the optical device according to example 1
20   through crossed Nicol prisms under the polarizing microscope with an electric field which changes unidirectionally from 0 kV/cm to -8.2 kV/cm being applied to the optical device. Fig. 10(a) shows an observation result obtained with no electric field applied. Fig. 10(b) shows an observation result
25   obtained by applying a -0.8 kV/cm electric field. Fig. 10(c) shows an observation result obtained by applying a -4.9 kV/cm electric field. Fig. 10(d) shows an observation result obtained by applying a -8.2 kV/cm electric field.

30   When an electric field which changes unidirectionally from 0 kV/cm to -8.2 kV/cm is applied in this way, a dielectric anomaly occurs when the electric field exceeds a predetermined dielectric anomaly threshold (-0.8kV/cm, in example 1), resulting in a polarization switching. The domain
35   structure of the PMN-PT changes accordingly. The dielectric

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anomaly caused by an electric field of -0.8 kV/cm can be observed from the graph in Fig. 8. When the applied electric field further increases in the negative direction, the optical transmission remains allowed and the relative permittivity
5   remains low while decreasing gradually.

In this way, even if the strength of the applied electric field is increased or decreased, the state which has a low permittivity and allows optical transmission is maintained.
10   In order for the PMN-PT to make a transition from the state which has a low permittivity and allows optical transmission to the initial state which has a high permittivity and blocks optical transmission, it is necessary to heat the device body to or above the Curie temperature.
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Figs. 14(a) to 14(c) show results obtained by observing the device body of the optical device according to example 1 through crossed Nicol prisms under the polarizing microscope with no electric field being applied after the optical device
20   is heated to or above the Curie temperature. Fig. 14(a) shows an observation result obtained at an extinction position, Fig. 14(b) shows an observation result at a stage rotation angle of 22.5°, and Fig. 14(c) shows an observation result at a stage rotation angle of 45°. As shown in Figs. 14(a) to 14(c), a
25   dark-field image is observed at any of the rotation angles. This shows that after being heated to or above the Curie temperature, the PMN-PT is in a state in which it blocks optical transmission.

30   Fig. 15 is a graph showing electric-field dependence of relative permittivity of the optical device according to example 1 after the optical device is heated to or above the Curie temperature. In Fig. 15, symbol Δ indicates points at which measurements are taken by varying an electric field in
35   the positive direction starting from zero. Symbol □ indicates

16

points at which measurements are taken subsequently by varying the electric field unidirectionally from positive to negative. Symbol × indicates points at which measurements are taken subsequently by varying the electric field unidirectionally

5   from negative to positive. Symbol o indicates points at which measurements are taken subsequently by varying the electric field unidirectionally from positive to zero. As shown in Fig. 15, after being heated to or above the Curie temperature, the PMN-PT has a relative permittivity as high as around 10,000

10 (9,000 to 12,000). However, when an electric field above the threshold is applied, the relative permittivity of the PMN-PT is approximately halved to 5,000 (4,000 to 7,000) by being reduced greatly. Once an electric field above the threshold is applied, the permittivity is kept low even if the electric

15 field is varied from positive to negative or from negative to positive.

     Fig. 16 is a graph showing electric-field dependence of relative permittivity of the optical device according to

20 example 2. In Fig. 16, symbol Δ indicates points at which measurements are taken by varying an electric field in the positive direction starting from zero. Symbol □ indicates points at which measurements are taken subsequently by varying the electric field unidirectionally from positive to negative.

25 Symbol × indicates points at which measurements are taken subsequently by varying the electric field unidirectionally from negative to positive. Symbol o indicates points at which measurements are taken subsequently by varying the electric field unidirectionally from positive to zero. As shown in Fig.

30 16, after being heated to or above the Curie temperature, the PMN-PT has a relative permittivity as high as around 10,000 (9,000 to 12,000). However, when an electric field above the threshold is applied, the relative permittivity of the PMN-PT is approximately halved to 5,000 (3,000 to 7,000) by being

35 reduced greatly. Again, with the optical device according to

17

example 2, as in the case of the optical device according to example 1, once an electric field above the threshold is applied, the permittivity is kept low even if the electric field is varied from positive to negative or from negative to
5   positive.

The device body of the optical device according to example 2 was observed through crossed Nicol prisms under the polarizing microscope with no electric field being applied.
10   Although not shown, it was confirmed that in the optical device according to example 2, the PMN-PT was in a state in which it blocked optical transmission.

Figs. 17(a) to 17(d) show results obtained by observing
15   the device body of the optical device according to example 2 through crossed Nicol prisms under the polarizing microscope by applying an electric field which changes unidirectionally from 0 kV/cm to 11.7 kV/cm and then unidirectionally from 11.7 kV/cm to 0 kV/cm. Fig. 17(a) shows an observation result
20   obtained with no electric field applied. Fig. 17(b) shows an observation result obtained by applying a 7.0 kV/cm electric field. Fig. 17(c) shows an observation result obtained by applying an 11.7 kV/cm electric field. Fig. 17(d) shows an observation result obtained with no electric field applied
25   after an 11.7 kV/cm electric field is applied once.

When an electric field above a threshold (3 kV/cm, in example 2) is applied, the PMN-PT in the device body makes a transition from a state in which it blocks optical
30   transmission to a state in which it allows optical transmission as shown in Figs. 17(b) to 17(d). At the same time, the PMN-PT exhibits a low relative permittivity (permittivity) as shown in Fig. 16. Even if the applied electric field further increases in the positive direction,
35   the optical transmission remains allowed and the relative

18

permittivity remains low while decreasing gradually.

When an electric field which changes unidirectionally
from 11.7 kV/cm to 0 kV/cm is applied to the optical device
5   according to example 2, the relative permittivity is kept at
as low as approximately 7,000 as shown in Fig. 16. At the
same time, the optical transmission remains allowed as shown
in Fig. 17(d).

10   The threshold at which the PMN-PT makes a transition from
a state which has a high permittivity and blocks optical
transmission to a state which has a low permittivity and
allows optical transmission varies between examples 1 and 2: 2
kV/cm in example 1 and 3 kV/cm in example 2. Generally, the
15   threshold increases with decreases in the composition ratio of
$PbTiO_3$ in the PMN-PT.

The embodiment described above may be changed as follows.

20   The optical device 10 may be embodied as an optical
memory. In that case, the optical memory stores information
as a binary signal of a state which allows optical
transmission or a state which blocks optical transmission.
The device body 20 exhibits a low permittivity when it is in a
25   state in which it allows optical transmission, and a high
permittivity when it is in a state in which it blocks optical
transmission. Consequently, by detecting differences in the
permittivity as voltage changes, it is possible to read stored
contents easily.
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Conventional techniques which use light to store
information include a magneto-optical disk. The magneto-
optical disk stores information as a binary signal in a
specific area on the medium by irradiating the specific area
35   with a laser beam, thereby heating the irradiated specific

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area to or above the Curie temperature, and then applying an external magnetic field when holding power of the specific area lowers, thereby magnetizing the specific area upward or downward. In this way, with the magneto-optical disk, the

5   magnetic field must be applied upward or downward distinctively after heating the specific area to or above the Curie temperature by irradiating it with a laser beam. On the other hand, if the optical device 10 is embodied as an optical memory, it is possible to switch between a state (ON) which

10 allows optical transmission through a specific area and a state (OFF) which blocks optical transmission, depending on whether or not the optical device 10 is heated to or above the Curie temperature.

15   The optical device 10 may be embodied as a light valve. In that case, the light valve controls entering light and outgoing light by switching between a state which allows optical transmission and a state which blocks optical transmission. The device body 20 exhibits a low permittivity

20 when it is in a state in which it allows optical transmission, and a high permittivity when it is in a state in which it blocks optical transmission. Consequently, by detecting differences in the permittivity as voltage changes, it is possible to detect operation of the light valve.

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        The device body 20 of the optical device 10 may be formed of PZN-PT or PIN-PT instead of PMN-PT.

        The optical device 10 may be used as an actuator which

30 utilizes piezoelectric characteristics of PMN-PT in addition to the optical characteristics and dielectric characteristics of the PMN-PT.